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LSP Composite Test Bed Design

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November 2013

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FOREWORD

The drawings shown this document were produced by Ken Griess of the Boeing Research & Technology (BR&T) Structures group. The general requirements and sensor configurations were researched and developed Art Day of the BR&T Applied Physics group, in consultation with Grant Erickson of BR&T Electromagnetics Effects.

The authors would also like to acknowledge Rob Steinle of the Boeing Test & Evaluation organization and Ed Rupke of Lightning Technologies, Inc. (Pittsfield, MA) for reviewing the design and providing valuable suggestions.

This revision provides the correct name of the company providing input to this document (mentioned above), and corrects typographical errors in section 4.6.2.

1 SCOPE

This document provides standalone information for the LSP Composite Substrate Test Bed Design. A six-sheet drawing set is reproduced here for reference, as is some additional descriptive information on suitable sensors and use of the test bed. The drawings will also be transmitted as separate PDF documents, and as digital files in DWG format for import into most CAD programs.

1.1 Purpose

The test bed design is deliverable 4.9 under the subject NASA contract and task order. The overall task order intent is to provide a Universal Common Practice Guide to Conduct Lightning Energy Transfer Characterizations, such that panels built to the set of specifications described in Reference 2.1.1 can be tested in one or more laboratories while ensuring a high level of consistency in test practices, test observations and data, and post-test evaluation methods.

1.2 Requirements for Test Bed Design

Requirements for the design, as given in the contract Statement of Work, are shown in the text box within Figure 1. These requirements have been met, with the exception that the method of measuring currents was changed per NASA technical direction, as will be discussed in Section 4.

The Contractor shall deliver an Engineering Design Drawing of an LSP Test Bed Fixture **(Deliverable Item 4.9)**. The design shall include the means to capture mechanical/electrical/thermal energy transfer parameters from the test article substrate during lightning strike tests.

This design shall include (at a minimum) the following:

- The LSP Test Bed shall be designed to accommodate a repeatable installation procedure to secure the test article substrate and eliminate test installation uncertainty for direct-effect testing.
- The test bed shall be designed to facilitate measurement of lightning current waveforms incident on the test article substrate. The Design shall include current sensor placement to facilitate 2D vector current mapping. Faraday-Effect optical current sensors and or Rogowski Coil current sensors shall be the method of capturing the electrical waveform parameters transferred onto the test article substrate.
- The Contractor shall define a thermal sensor capable of capturing required thermal parameters and be resilient to lightning energy.
- The Contractor shall define a mechanical sensor capable of capturing required mechanical parameters and be resilient to lightning energy.
- The sensors shall operate with repeated exposure in lightning environments.
- The sensor's operational parameters (i.e., acquisition speed, bandwidth, and performance resolution) shall be defined to meet requirements to support high-fidelity modeling.
- LSP Test Bed fixture shall be designed to facilitate evaluations to determine induced current for systems located in the vicinity of regions where electromagnetic coupling is present.
- The design shall include specifications to allow unity-correlation between future data sets.

Figure 1: Excerpt from Statement of Work, with requirements for the Test Bed Design.

2 REFERENCES

2.1 Applicable Documents

- 2.1.1 NASA Document # DOC-128694 – LSP Composite Substrate Manufacturing Processing Guide**
- 2.1.2 NASA Document # DOC-128695 - LSP Composite Substrate NDE Assessment Manual**
- 2.1.3 NASA Document # DOC-128695 - LSP Composite Substrate Lightning Test Operations Guide**
- 2.1.4 NASA Document # DOC-128697 – LSP Composite Substrate Destructive Evaluation Test Assessment Manual**
- 2.1.5 SAE ARP5412A – Aircraft Lightning Environment and Related Test Waveforms Rev A**
- 2.1.6 SAE ARP5416 – Aircraft Lightning Test Methods**

Parties interested in acquiring a copy of these documents and the data generated from this test effort are invited to contact the AEST Task Monitor, George Szatkowski, at his email address (george.n.szatkowski@nasa.gov) or phone number (757-846-6149).

2.2 Nomenclature

AEST - Atmospheric Environment Safety Technologies

AI - Action Integral

ARP - Aerospace Recommended Practice

CFRP – Carbon Fiber Reinforced Plastic

EME – Electromagnetic Effects

FAA – Federal Aviation Administration

LSP – Lightning Strike Protection

NIST – National Institute of Standards and Technology

OML – Outer Mold Line (smooth Tool Side of Lay-up, this side is painted, and is also the side to be directly exposed to simulated lightning currents)

SAE - Society of Automotive Engineers

3 TESTBED DRAWINGS

The test bed design is defined by Drawing No. 128698 sheets 1 – 6. It is shown in Figures 2 – 7 below. The drawing includes one page of drawing notes as Sheet 1 (Figure 2). The notes page includes descriptions of recommended materials and construction techniques. The builder of a test bed per this design may be allowed some leeway in materials and techniques, provided that the resulting structure has a comparable rigidity and does not introduce unintended electrical conduction paths. The notes page also includes model numbers for suggested current monitors and displacement sensors, for which mounting provisions are made directly on the test bed structure. Thermal sensing is expected to be by an infrared camera which is not mounted directly on the test bed but is able to view the panel IML surface from a distance of approx. 3 m.

Assembly drawings are shown on Sheet 2 (Figure 3). The basic construction is a fastened plywood box, with large open areas for access by cameras, cabling, and sensors. Plywood is inexpensive and easily worked, and is of sufficiently low conductivity for most lightning test work. For sensor access, it will typically be most convenient to mount the box and panel vertically as shown in the isometric view. However, the box could easily be turned for horizontal panel testing.

The test panel is to be mounted over a wide aperture in part no. 128698-2 and secured by nine toggle clamps, part nos. -6, which apply pressure to the grounding bars. With four of these clamps, copper straps can be clamped to the grounding bars on each side of the panel. Descriptions of recommended grounding arrangements and strap sizes can be found in Reference 2.1.3. The assembly drawing shows four Pearson 4418 Current Monitors (part no. -8) affixed to the front of the box, positioned so that copper straps can be led to each of the four sides while maintaining equal strap lengths. Additional mounting locations for current monitor mounting are also shown, which may be convenient for the tester but are not required.

Three Keyence LK-G507 optical vibration sensors are shown in the assembly drawing as part no. -7. These are held by part nos. -5 (“Keyence Holder”), which are in turn mounted on the back panel, part no. -4. The Keyence Holders are designed so that these sensors can be moved laterally on the back panel. The holders also provide for rotation of the sensor beam in the vertical direction, so that most areas of the panel OML will be accessible for vibration measurements.

Detailed dimensioned drawings are on Sheets 3 - 6 (Figures 4 – 7).

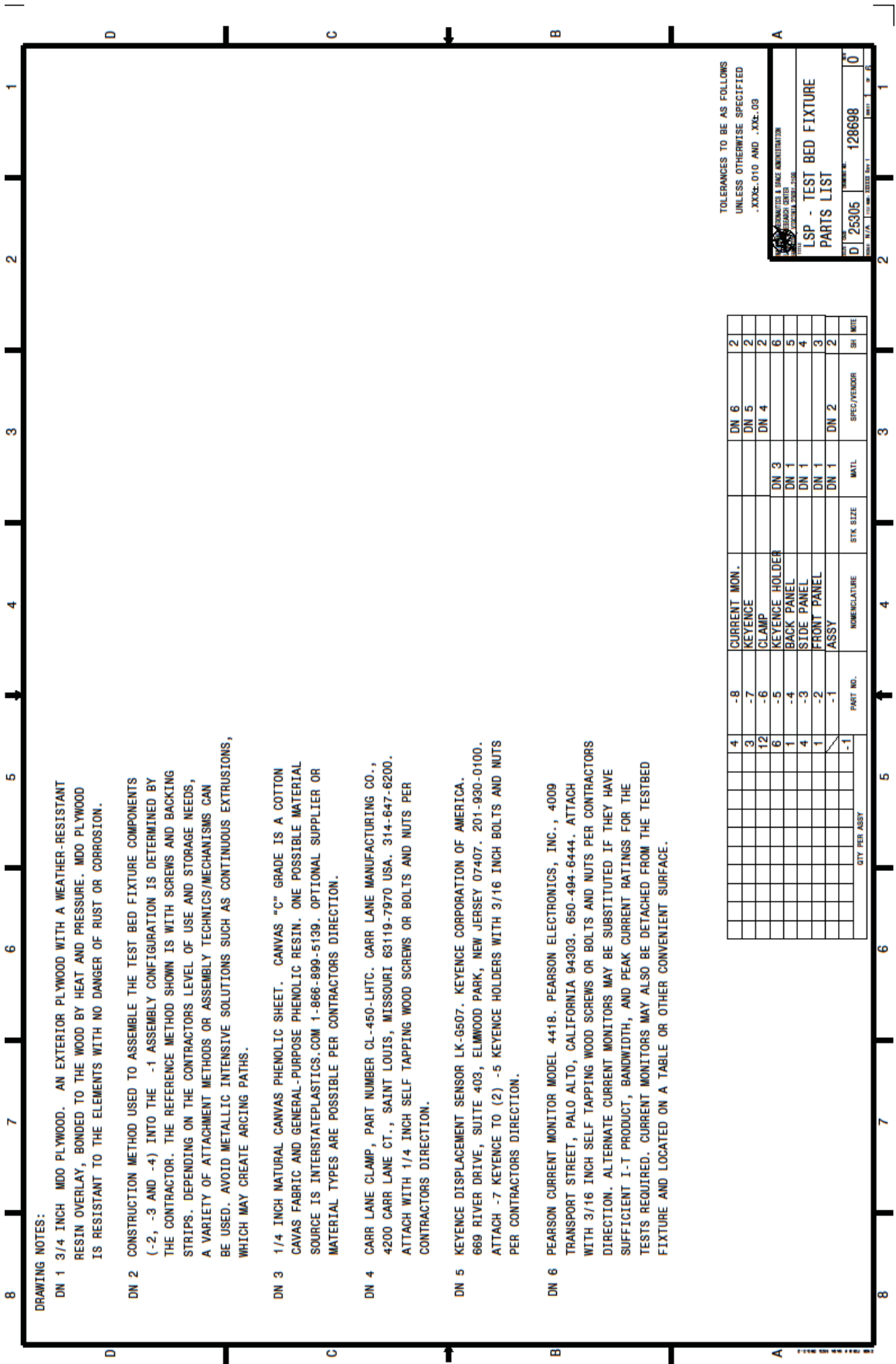


Figure 2: LSP Test Bed drawing (sheet 1 of 6)

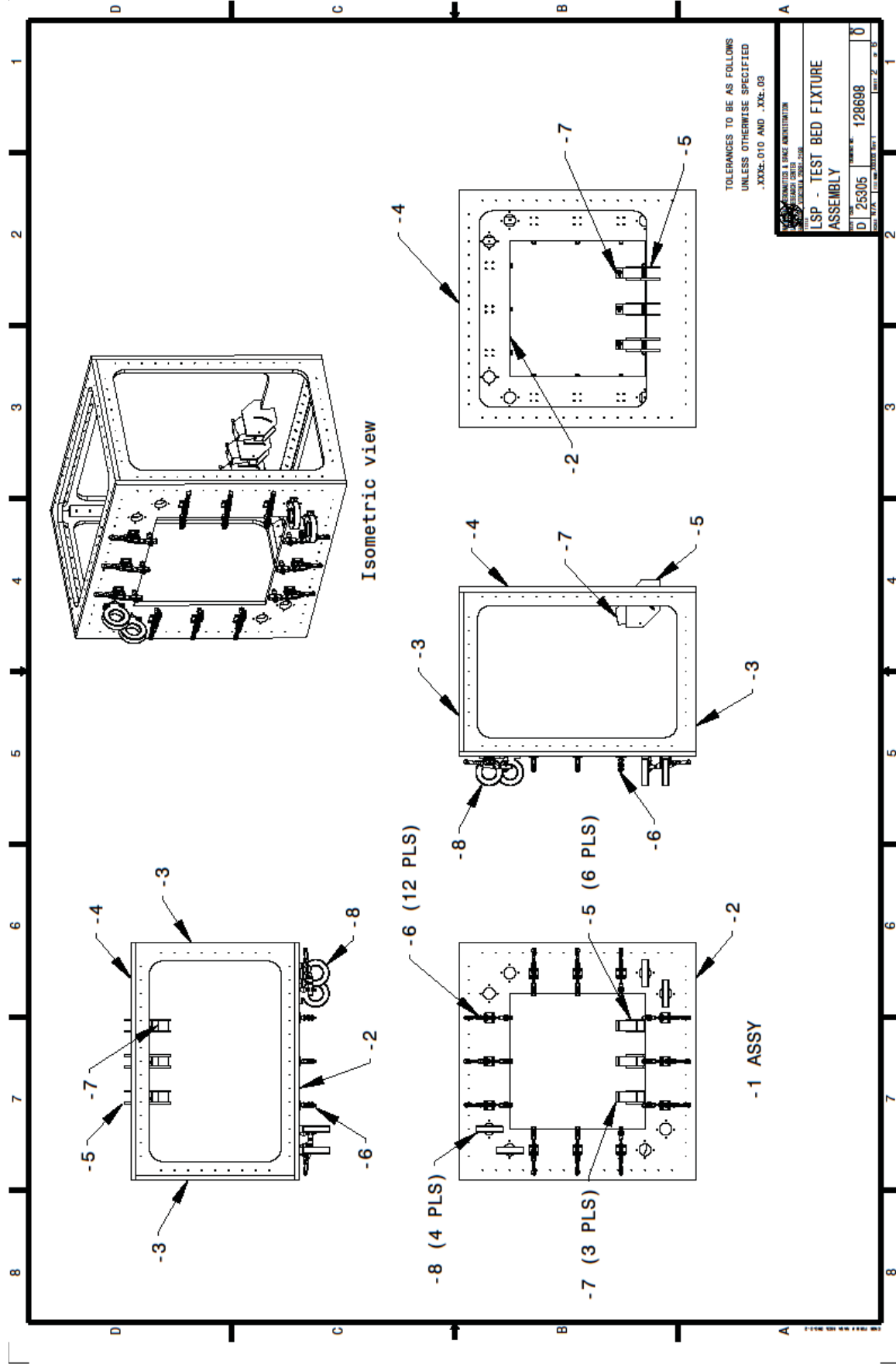
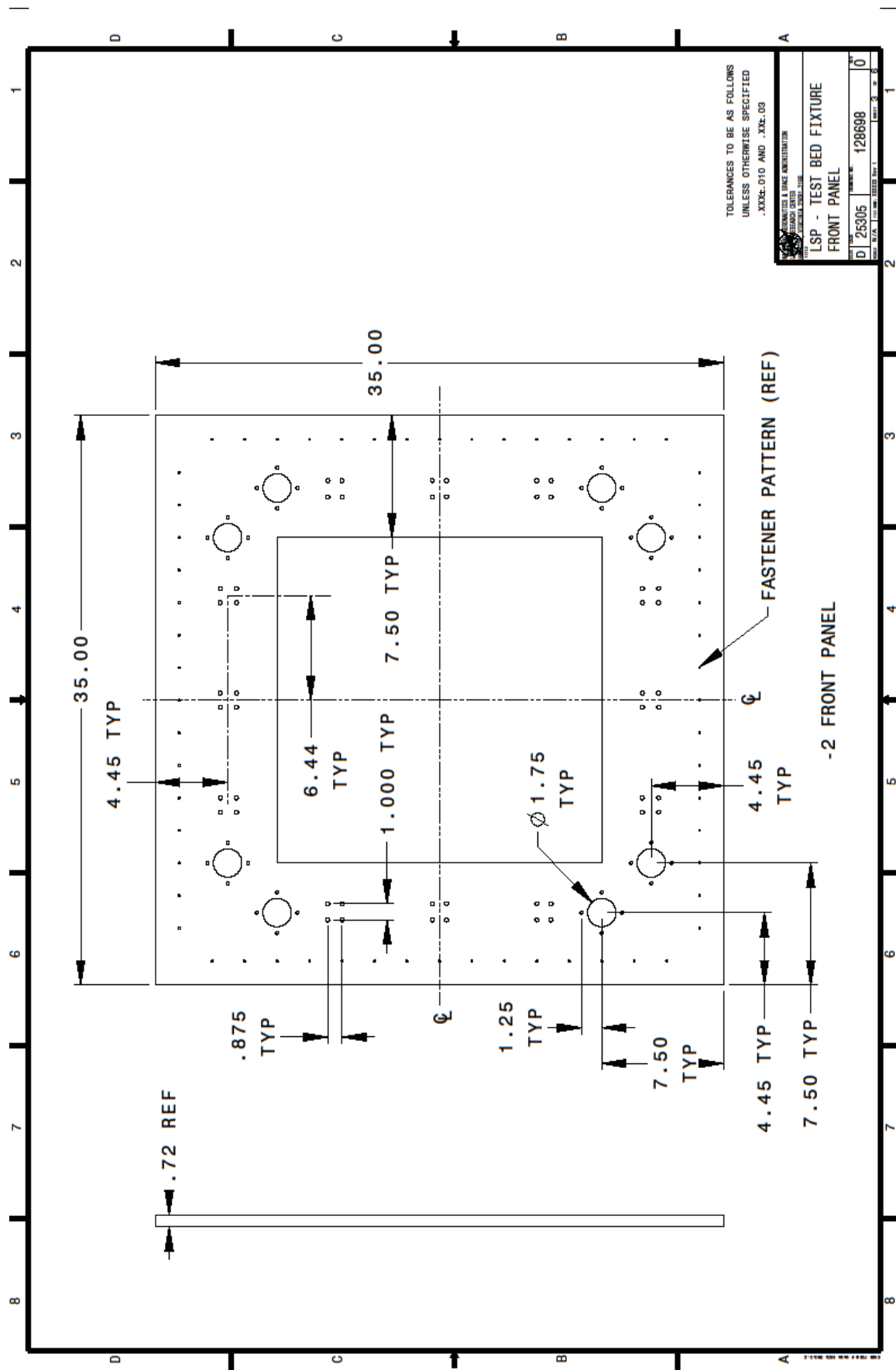


Figure 3: LSP Test Bed drawing (sheet 2 of 6)



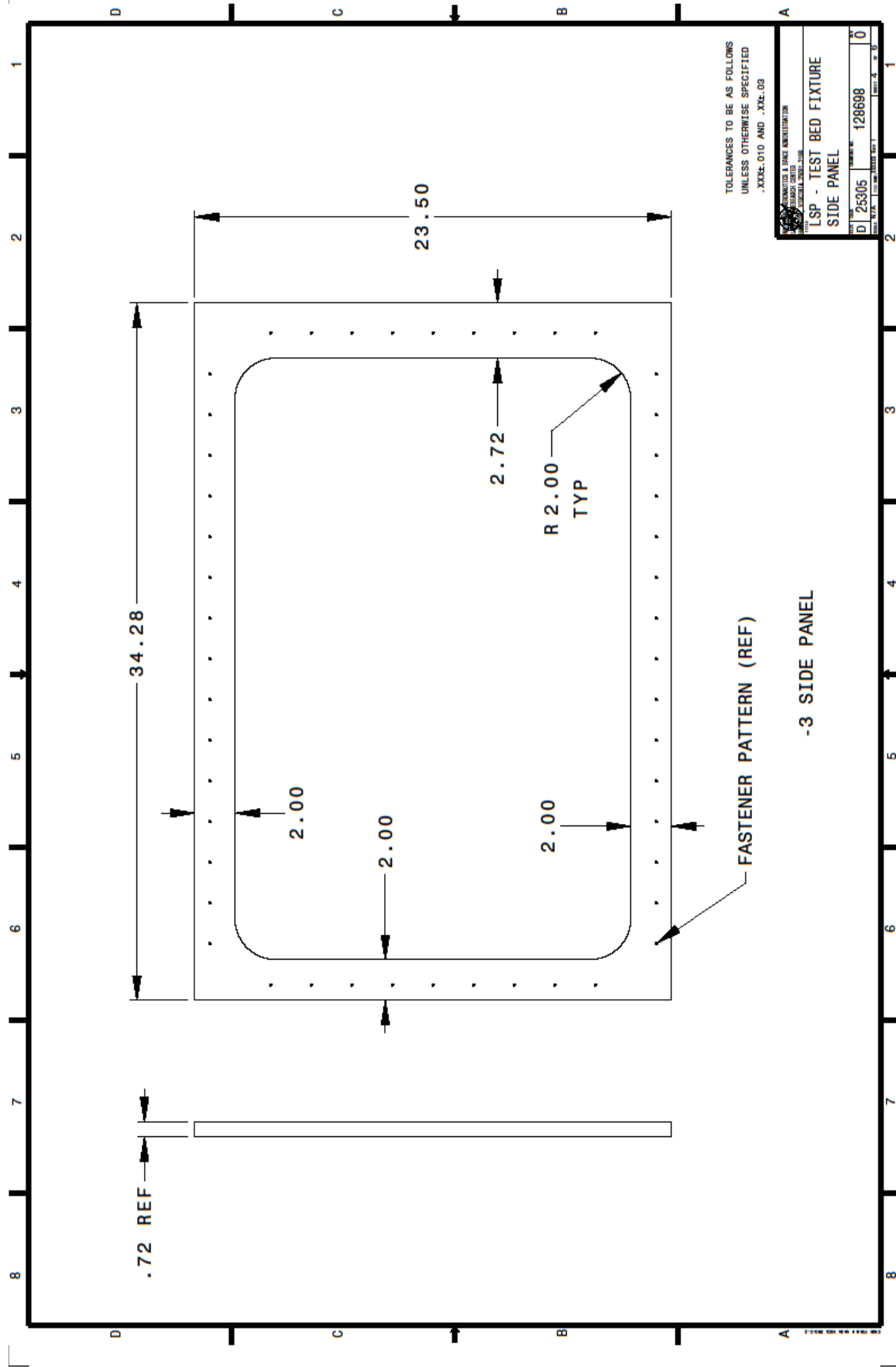


Figure 5: LSP Test Bed drawing (sheet 4 of 6)

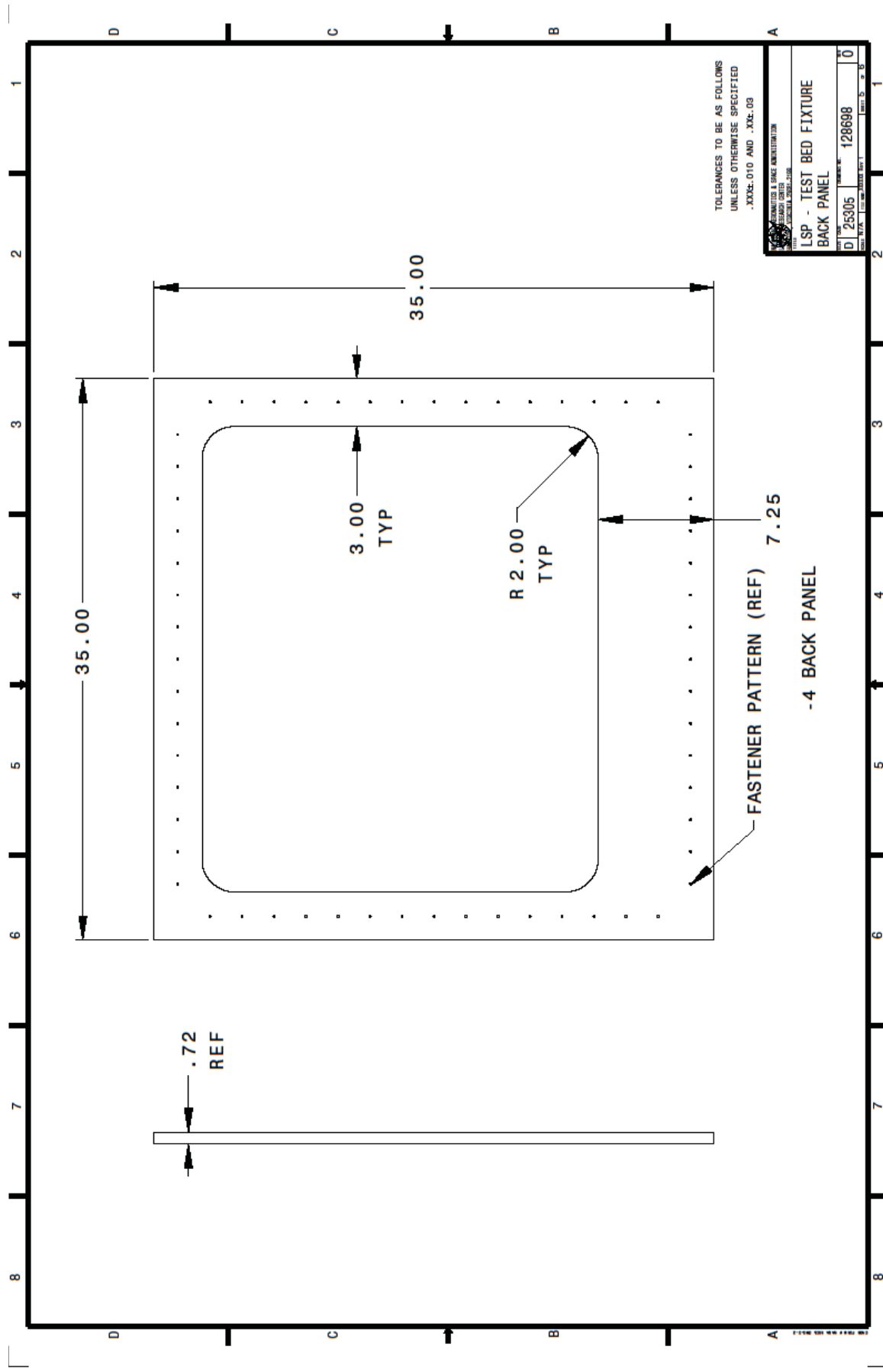


Figure 6: LSP Test Bed drawing (sheet 5 of 6)

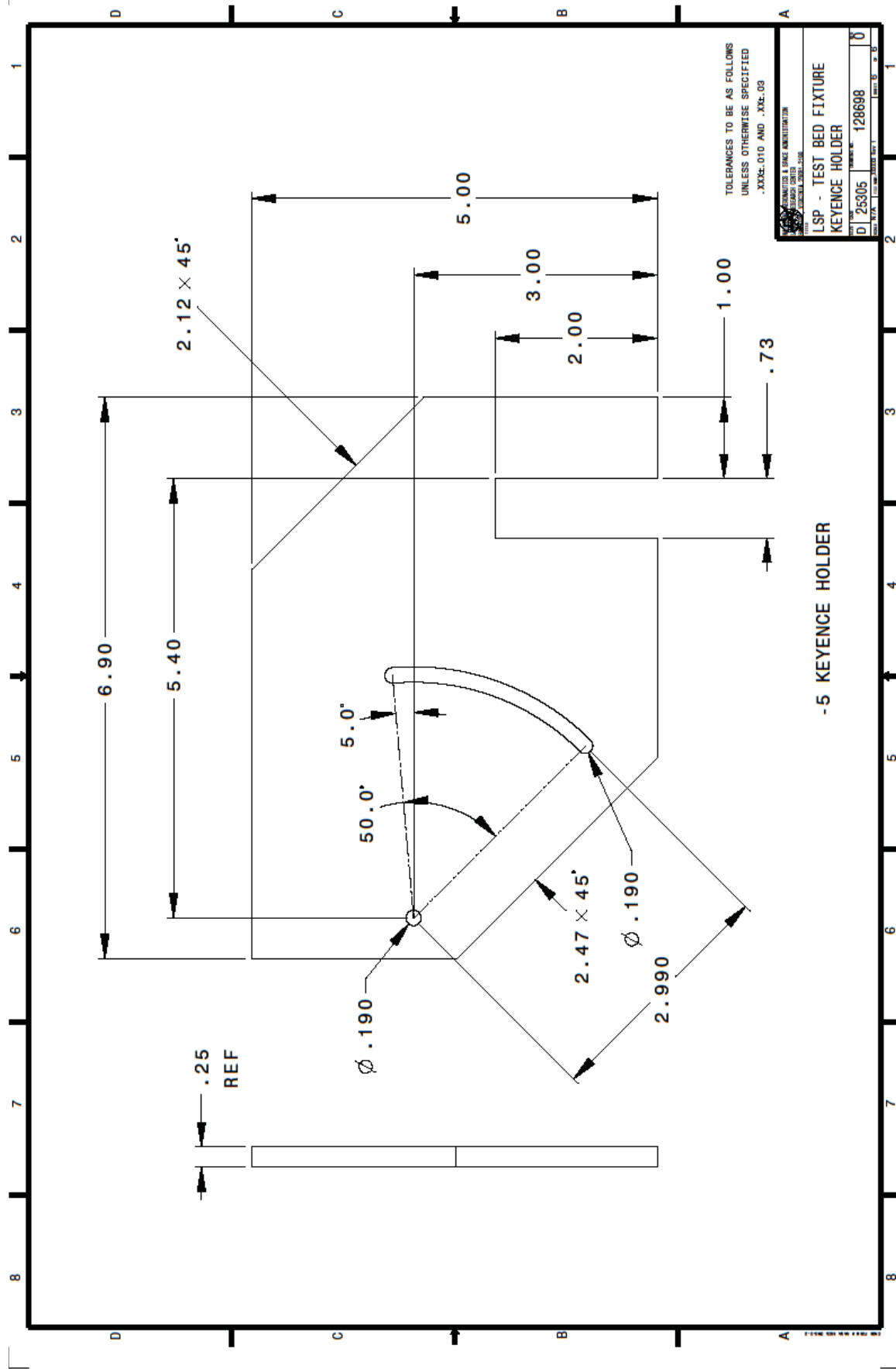


Figure 7: LSP Test Bed drawing (sheet 6 of 6)

4 ADDITIONAL OPERATIONAL INFORMATION AND SPECIFICATIONS

4.1 Installation features

The toggle clamps specified provide up to 500 lb. each of clamping force. The symmetric positioning of the clamps around the periphery of the part will provide for easy, repeatable positioning. The clamp face pulls away entirely from the clamped surface so that the panel can be inserted or removed without interference.

4.2 Current waveform sensing

The test bed design envisions that up to four edges of a test panel may be independently grounded and sensed. Based on the intended peak current test levels of 100 kA, 40 kA, and 20 kA, a Pearson 4418 was selected as an appropriate current monitor. Pearson current monitors are widely used in lightning and pulsed-power labs. The 4418 is rated for a peak current of 200 kA and a total charge transfer capability (I-T product) of 6 Coulomb when biased, or 2 Coulomb without biasing. When testing with lightning waveforms B and C, the user should check the detected charge transfer to be sure that these limits are not exceeded, or inaccuracy may result. The user should also take care that these monitors are not subject to high fields and voltages, since they are single-isolated rather than double-isolated. It is common practice (and recommended) to wrap a thick Mylar sheet around grounding straps where they feed through current monitors.

Other current probes such as the Pearson 1423 could be used in place of the 4418. These provide higher I-T product, but are significantly larger and would have to be located on a secondary support. In such cases, the user should keep the grounding strap lengths from changing beyond the limits described in Reference 2.1.3.

The SOW for this task called for use of Faraday Effect current or Rogowski current probes. The NASA technical focal originally expected that the test bed would accommodate one or more such probes which were under development at NASA, but in the course of monthly progress meetings, Boeing was told that these probes were not now ready for this application. The use of Pearson-type probes was discussed and agreed to at one of the monthly Boeing/NASA telecoms.

4.3 Thermal Sensing

Thermal data have been used at Boeing and elsewhere as a diagnostic to quantify energy deposition on test panels and other evaluation purposes. Boeing has been successful in using a SC640 ThermaCAM from FLIR Systems, including through approximately 20 lightning tests. This model can be battery-operated and, if desired, the data can be streamed to a laptop computer over a FireWire connection. Basic specifications are given in Table 1 below. Based on Boeing experience, IML temperature profiles can be accurately sensed with frame rates on the order of 2/second, so the SC640 is more than adequate. Very advanced users may wish to conduct thermography on the OML as well, but the risk of plasma flash damage to IR equipment is such that these users will have to develop their own operational requirements depending on the experimental conditions.

Table 1: FLIR Systems SC640 specifications

Property	Specification
Temperature range	-40C to 1600 C
Thermal sensitivity	< 0.08 C at 30 C
Accuracy	+/- 2C or 2% of reading
Spatial resolution	0.66 mrad (40 mm lens)
Detector	Uncooled μ bolometer
Spectral range	7.5 – 13 μ m
Image frequency	30 frames/second

In the Boeing application, both the camera and a laptop were placed in a lightly shielded wooden box, with a hole cut for lens access. Shielding consisted of medium-duty aluminum foil. The camera was located approximately 3 m behind the test panel. A photo of the lab setup is shown in Figure 8 and a photo of the box (with an access door removed) in Figure 9. Further information on usage is given in Section 4.6.



Figure 8. Boeing Lightning Laboratory with test panel (left) and shield box for camera and laptop (right)

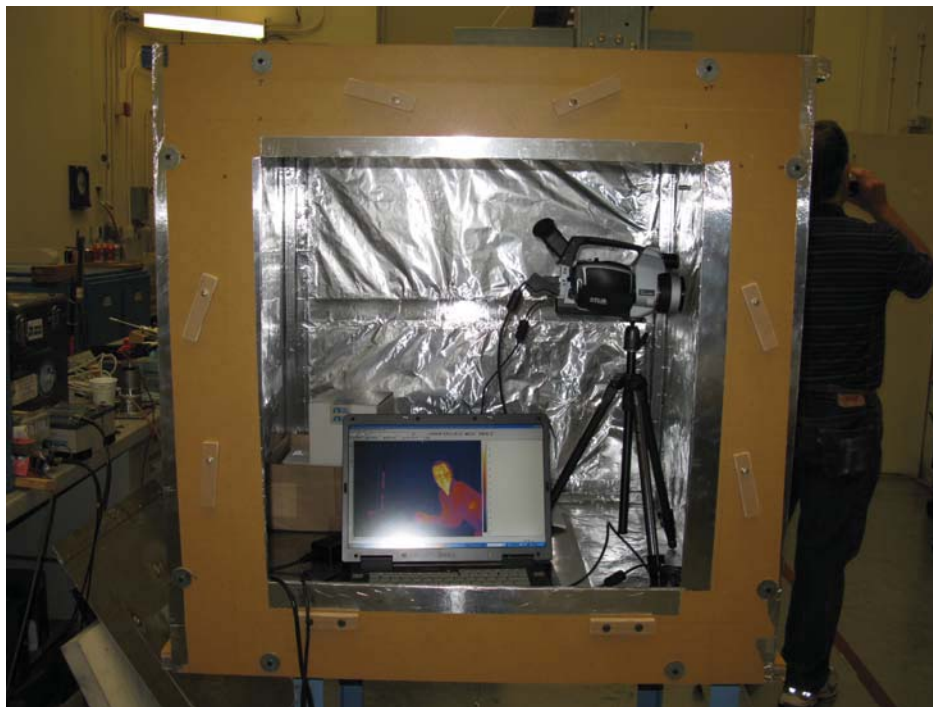


Figure 9: Shield box with camera and laptop, with access door removed.

The data obtainable with this system in lightning tests can be accurate to within a few degrees C and provide high spatial resolution. Two examples are given in figures 10 and 11 below.

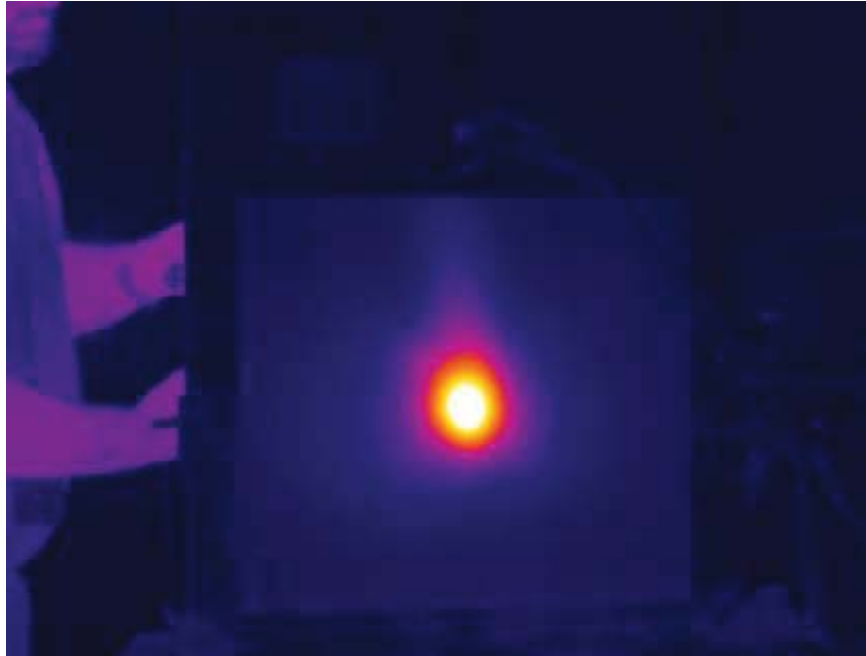


Figure 10: IML temperatures following a typical test. Peak temperature = 81C.

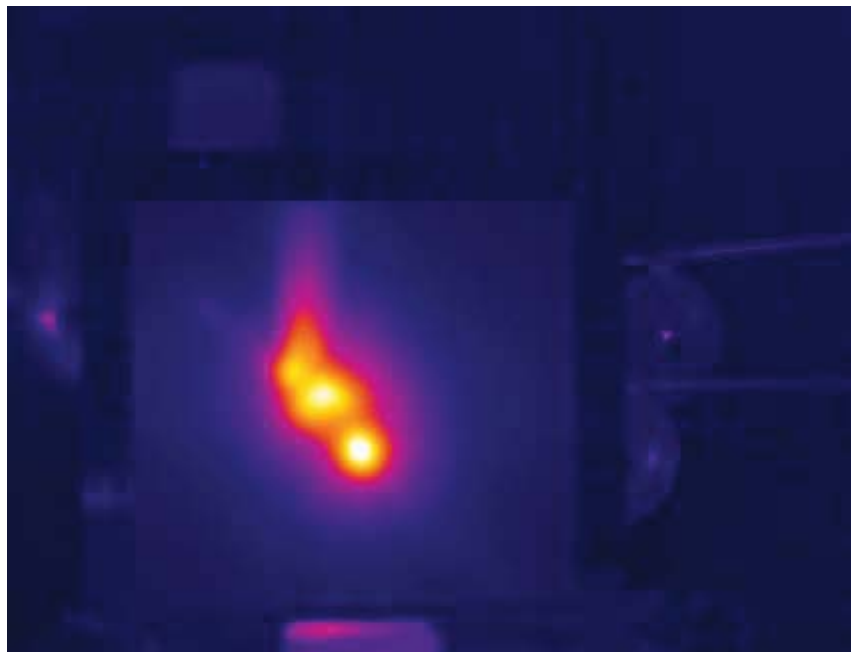


Figure 11: Unusual IML thermal pattern resulting from flaming fibers on OML.

4.4 Mechanical Sensing

The mechanical response of a panel under lightning strike can be highly variable, depending on thickness and sometimes added systems or stiffening structures. Shock effects may have a bearing on panel puncture. When underlying systems are part of a test, it is especially important to guard against unintended forces and deflections of such systems toward the panel due to inductive effects.

A trial was made of a high-bandwidth optical position/vibration sensor in the Boeing Lightning Laboratory. The sensor was the LK-G507 from Keyence. The sensor operated through repeated strikes of up to 100 kA (full Zone 2A) using the setup shown in Figure 12. The sensor is approximately 20" behind the test panel, and a cable leads to a laptop which is operated on battery power. The sensor is also powered by a 24 V power supply, which for this test was operated from an Uninterruptible Power Supply (UPS). A position waveform from the sensor is shown in Figure 13 as it appeared on the laptop screen.



Figure 12: Test run of Keyence optical position/vibration sensor.

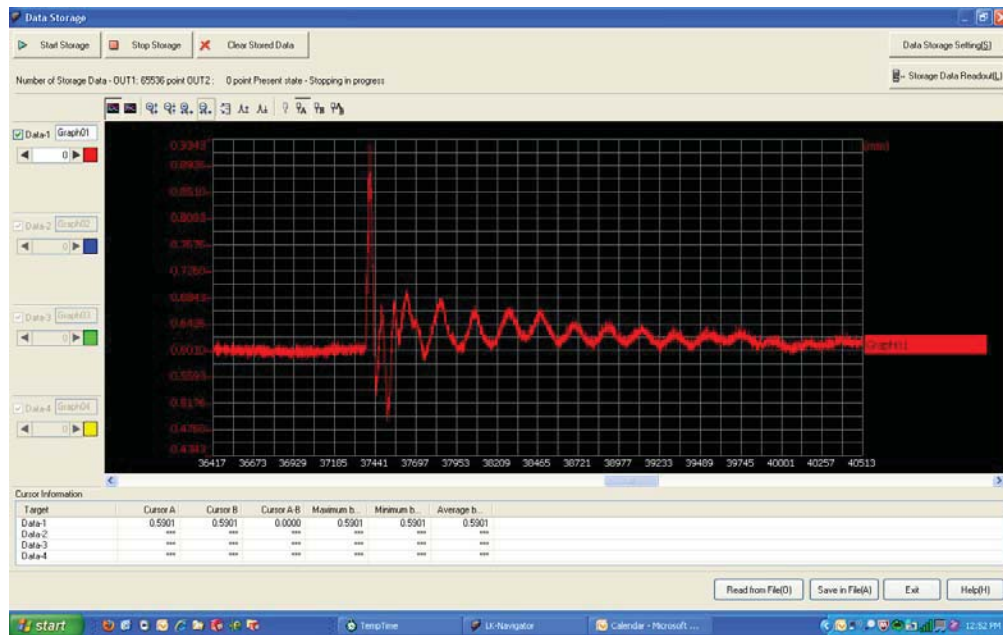


Figure 13: Position vs. time on Keyence sensor. Bandwidth for this run = 1 kHz.

To support high-fidelity modeling, it is recommended that vibration sensor have a bandwidth that is at least 1 kHz, which will typically allow it to sense lower-order vibration modes of a panel. The Keyence LK-G507 can theoretically attain 50 kHz although at Boeing no tests were run above 10 kHz. It should also have a spatial resolution of 0.1 mm or better.

Setup for laser-reflection sensors will typically consist of mounting the sensors to the rear face of the test bed. The Test Bed provides a design for holding plates for up to three Keyence model LK-G507 sensors, such that their output beams can be adjusted to the desired sense point. These sensors send data directly to a portable computer which should be operated on battery power during a test.

4.5 Ability to Operate with Repeated Exposure to the Lightning Environment

As described above, both the FLIR Systems IR camera and the Keyence optical sensors have been checked in the Boeing Lightning laboratory. Repeated shots were done with these sensors operating properly and showing no damage or degradation in performance. Current probes similar to the Pearson 4418 have also been operated in the Boeing laboratory for many years. As with any high-voltage test, poor lab practices can result in equipment failures or serious injuries. To the best of our knowledge the sensors described herein are not

particularly sensitive to EMI but can be operated successfully by prudent engineers familiar with lightning test environment.

Setup for an IR camera will typically require a camera to be mounted on a tripod and located approximately 3 meters behind the test panel. It may also be connected to a portable computer so that a video stream can be recorded over several minutes. To prevent interference or damage during the test, both of these should be operated on battery power. It is further recommended that they should be located in a box that provides some shielding against high frequencies. Medium-gauge aluminum foil has been found suitable but results may vary with camera and computer models.

4.6 Operating Parameters to Support High-Fidelity Modeling

Boeing's approach to this question is necessarily subjective, but the general approach taken has been to design a test bed that provides features for testing and modeling which are as good as or better than anything we are aware of in the leading laboratories today. Characteristics of recommended sensors have been described in previous sections of this document, and are more fully detailed in manufacturer's operating manuals. Other operating parameters for testing have been well-described in the other documents produced under this Task Order, which are listed as references in Section 2.

4.6.1 Surface Emittance Determination

If IR thermography is used to record panel surface temperatures following a test strike, accuracy of the temperature depends on having a valid estimate of the surface's thermal emittance. For paints and composites, this number is typically between 0.7 and 0.95. This number should be measured (the preferred method) or otherwise determined to an accuracy of $\pm 5\%$, or errors of 10 degrees Celsius or more may result. An infrared reflectance or emittance measurement is needed to determine the thermal emittance, since optical properties in the thermal IR (the 8 – 14 micron wavelength band seen by most IR cameras) can be very different from the properties at visual wavelengths. Suitable instruments for measuring emittance include the Gier-Dunkle DB100 and the AZ Technology TEMP 2000A. It is also acceptable to apply a known high-emittance paint to the back of a panel, rather than (or on top of) standard aircraft paints. A thin layer less than .010" thick will result in no detectable change in surface temperature over the multi-second heating that is to be expected.

4.6.2 Additional Operating Suggestions for Sensors during Simulated Lightning Attachments

This section includes typical procedures for IR and optical vibration sensors, but actual procedures may require some modification based on the specifications and operating manuals of the available equipment.

The IR and vibration sensors described in the sections above can both be operated via battery-operated laptops that are located in the test cell. Data acquisition can be started and personnel evacuated from the cell prior to charging the banks.

Prior to initiating the data sequence, focus the IR camera on the rear of the test panel. Enter settings in the camera or its dedicated software package for the panel's surface emissivity, as well as distance, room temperature, and humidity. The data storage rate (in frames per second) may be adjustable and rates from 1 frame per second to 30 frames per second may be suitable because CFRP panels typically require 10 seconds or more to reach maximum temperature on the OML. Verify that the camera shows room-temperature objects to be within +/- 3 degrees Celsius of the known ambient temperature. Unplug the camera and associated computer from line power. Initiate data streaming from the camera to the computer.

Prior to initiating data acquisition, locate optical vibration sensors so that the laser spot is directed to the desired location for the vibration measurement. The Test Bed allows freedom of lateral positioning of the sensor bodies on the rear panel of the box, and freedom of the vertical beam alignment by rotating the sensor bodies on a holding plate. Set the frequency response of the sensor via its associated control software: Typically, 1 kHz will be sufficient. Set the acquisition time window to a value that will allow for vacating the room and for the charge and discharge times of the test current generator. Initiate data streaming from the sensor(s) to the computer.

4.7 Ability to Evaluate Induced Current Effects for Systems Near the Test Panel

Aircraft systems runs are often located in close proximity to aircraft skins, and these may be subjected to transient fields and forces when simulated lightning testing includes such systems. Because systems vary enormously in size, shape, and distance requirements, no special fixturing has been built into the LSP Substrate Test Bed. However, the test bed box allows easy access to the back of

the test panel through all four sides. C-clamps can be used to hold additional cross-pieces to the box for mounting of tubes or cables. Alternatively, the box can be modified with the most basic hand or power tools.

4.8 Additional Comments Regarding Unity-Correlation

Boeing has striven to keep the test bed design simple, while also allowing some flexibility for operator convenience. The instrumentation recommended here was selected based on practicality and affordability for an ongoing lightning test operation. The procedures and specifications in the referenced documents should be sufficient for enabling a high degree of correlation of results between testers.

Ultimately, the ability to correlate results from one laboratory to another rests with the operators and with the coordination given them. In particular, any deviations from the referenced documents or from manufacturer's recommendations should only be allowed if justified by sound engineering analysis of such deviations, and documentation of the rationale.

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